Intensive Care Med
https://doi.org/10.1007/s00134-026-08341-5

UNDERSTANDING THE DISEASE

Understanding lung physiology through ventilator screen

Guillaume Carteaux[1,2,3*], Elena Spinelli[4] and Samir Jaber[5,6]

© 2026 Springer-Verlag GmbH Germany, part of Springer Nature

One of the major technological advances of recent decades in mechanical ventilation has been the advent of screens displaying airway pressure and flow waveforms, transforming ventilators into powerful tools for bedside monitoring and functional exploration of the respiratory system. When properly interpreted, ventilator waveforms provide continuous real-time information on respiratory mechanics and patient–ventilator interactions, allowing clinicians to customize ventilator's settings. This article focuses on passive patients, defined by the absence of clinically meaningful inspiratory effort capable of triggering or distorting ventilator-delivered breaths, with a primary emphasis on volume-assist control ventilation (ACV) using constant inspiratory flow.

Airway pressure waveform at a glance

Equation of motion of the respiratory system

In passive patients, airway pressure (P_{aw}) waveform during insufflation follows, at any time (t) during the inflation, the equation of motion of the respiratory system [1]:

$$P_{aw}(t) = P_0 + P_{res} + P_{el} = P_0 + R_{RS} \times \dot{V}(t) + E_{RS} \times V(t)$$

where P_0 is the end-expiratory alveolar pressure, corresponding in practice to the total positive end-expiratory pressure (PEEP), Pres is the resistive pressure, P_{el} is the elastic pressure above P_0, R_{RS} is the resistance of the respiratory system, $\dot{V}$ is the airflow, E_{RS} is the respiratory system elastance (the mathematical inverse of the compliance, C_{RS}), and V is the insufflated volume. Normal and altered values of E_{RS}, C_{RS}, and R_{RS} are detailed elsewhere [1]. End-inspiratory and end-expiratory occlusion maneuvers allow estimation of alveolar pressures and separation of elastic and resistive components of airway pressure (Fig. 1A). Thus, during ACV, the airway pressure waveform provides immediate physiological information, if the plateau pressure is monitored (Fig. 1A).

Conductive pressure

Conductive pressure (P_{cond}) corresponds to the abrupt early rise in airway pressure at the onset of insufflation, before any significant volume has entered the lungs [2]. It represents the pressure required to conduct gas from the ventilator circuit to the alveoli and should theoretically equal the Pres measured at end inflation, that is, peak pressure minus plateau pressure, measured after a brief (300–500 ms) end-inspiratory occlusion (Fig. 1A). Pcond exceeds Pres in two situations [3]. The first is intrinsic PEEP (PEEPi), where inspiratory flow becomes positive only once Paw surpasses the total PEEP; in that case, $P_{cond} = P_{res} + \text{PEEPi}$. The second is the airway closure above the applied PEEP, where flow begins only when P_{aw} reaches the airway opening pressure (AOP). In that case, $P_{cond} = P_{res} + (\text{AOP} - \text{PEEP})$ (Fig. 1B). An end-expiratory occlusion maneuver allows differentiation between these two mechanisms [3]. Conversely, when P_{cond} and P_{res} are equal, the presence of an AOP above PEEP can be ruled out, with a negative predictive value exceeding 95% [2]. These distinctions are clinically relevant because unrecognized airway closure may lead to overestimation of the driving pressure and inappropriate ventilator settings.

Stress index

The shape of the airway pressure curve during tidal inflation under constant flow can be described using the following equations [4, 5]:

*Correspondence: guillaume.carteaux@aphp.fr
[1] Service de Médecine Intensive Réanimation, Assistance Publique-Hôpitaux de Paris, CHU Henri Mondor-Albert Chenevier, Créteil, France
Full author information is available at the end of the article

SHOUT
SHARE
IT

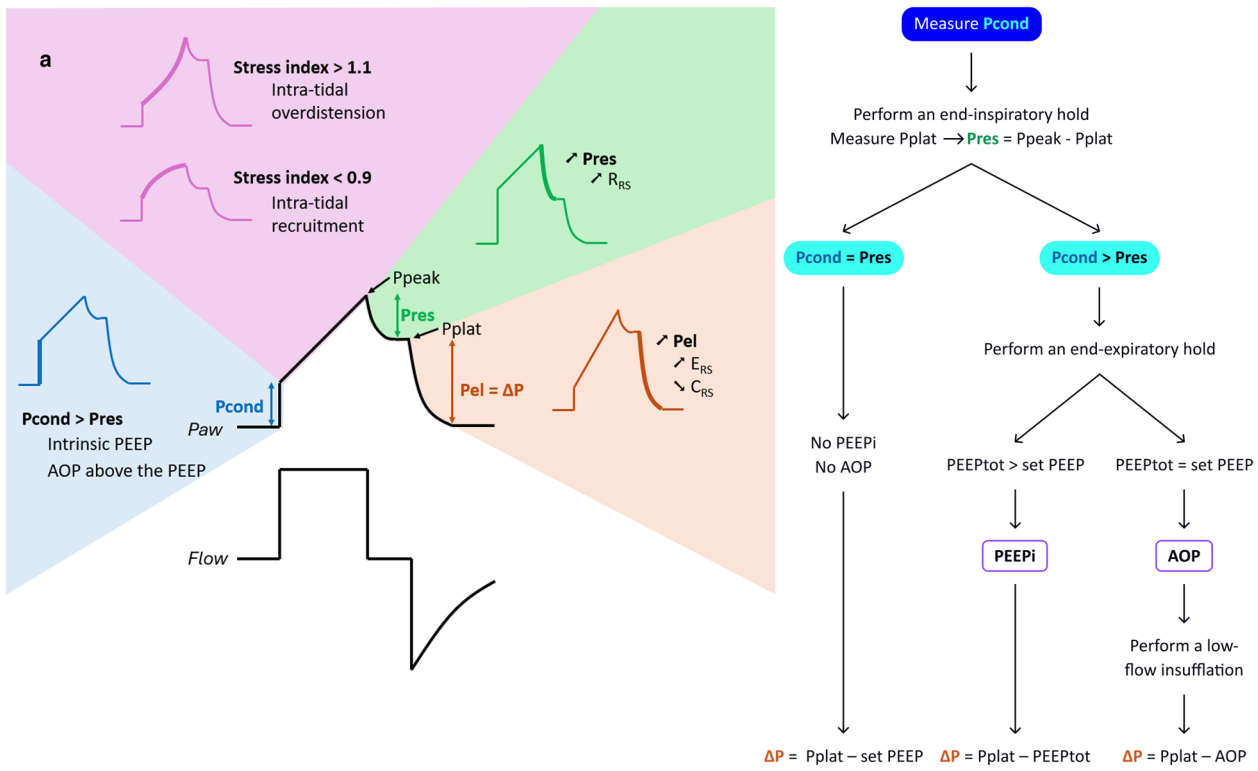

Fig. 1 Ventilator waveform analysis and dynamic maneuvers. **A** Airway pressure waveform at a glance. Inspection of the airway pressure (P_{aw}) waveform during volume-assist control ventilation provides information on the presence of intrinsic PEEP or airway opening pressure (AOP) above applied PEEP, intratidal recruitment or overdistension, excessive strain, and respiratory mechanics (see text for details). The right panel provides a step-by-step guide for interpreting the conductive pressure (P_{cond}). Note that when P_{cond} exceeds the resistive pressure (P_{res}), the observed driving pressure (ΔP) systematically overestimates the actual ΔP. On some ventilators, however, conductive pressure may be difficult to measure, particularly when inspiratory flow is not strictly constant. **B** Low-flow insufflation maneuver used to detect and measure a potential AOP. Left panels show pressure–volume curves; right panels show pressure–time curves. The pressure–volume curve is automatically generated by some ventilators. To obtain a pressure–time curve when the ventilator does not provide a pressure–volume loop, the following steps can be performed: (1) reduce the respiratory rate to approximately 8 breaths per minute; (2) reduce the inspiratory flow to 5 L/min. **C** Single-breath maneuver allowing calculation of the volume recruited by PEEP (V_{rec}). The maneuver is performed after at least 10 min at high PEEP (e.g., PEEP 15 cmH_2O). The following steps are then performed: (1) reduce the respiratory rate to 8–12 breaths per minute; (2) record the expired tidal volume at high PEEP; (3) decrease PEEP (e.g., to 5 cmH_2O); (4) record the expired tidal volume of the breath in which insufflation occurs at high PEEP and expiration at low PEEP; and (5) measure plateau pressure at low PEEP to calculate C_{RS}. P_{cond} conductive pressure, P_{peak} peak pressure, $_{Pplat}$ plateau pressure, P_{res} resistive pressure, P_{el} elastic pressure above end-expiratory pressure, ΔP driving pressure, R_{RS} respiratory system resistance, E_{RS} respiratory system elastance, C_{RS} respiratory system compliance, $\Delta PEEP$ change in PEEP between high and low levels, $V_{Te\,high \rightarrow lowPEEP}$ expired volume collected during the breath transitioning from high to low PEEP, $C_{RS_lowPEEP}$ respiratory system compliance at low PEEP, V_T tidal volume

$$P_{\mathrm{aw}} = a \times time^{b} + c$$

The exponent b of this equation, called the stress index, characterizes intratidal changes in compliance. A stress index between 0.9 and 1.1 corresponds to a linear pressure–time profile [6] and indicates stable compliance during insufflation, which is the desired condition. A stress index below 0.9 is characterized by an upward convex shape, reflecting increasing compliance during inflation and suggesting intratidal recruitment, a situation that should prompt an increase in PEEP. Conversely, a stress index above 1.1, recognizable by an upward concave curve, reflects decreasing compliance during inflation and suggests tidal overdistension, indicating a need to reduce either PEEP or tidal volume (Fig. 1A). Thus, stress index analysis provides continuous, dynamic information on intratidal lung behavior without interrupting ventilation. It should be noted that the stress index does not inform on regional lung heterogeneity.

Driving pressure

Elastic pressure above end-expiratory pressure, also referred to as driving pressure (Fig. 1A), has major physiological significance in acute respiratory distress

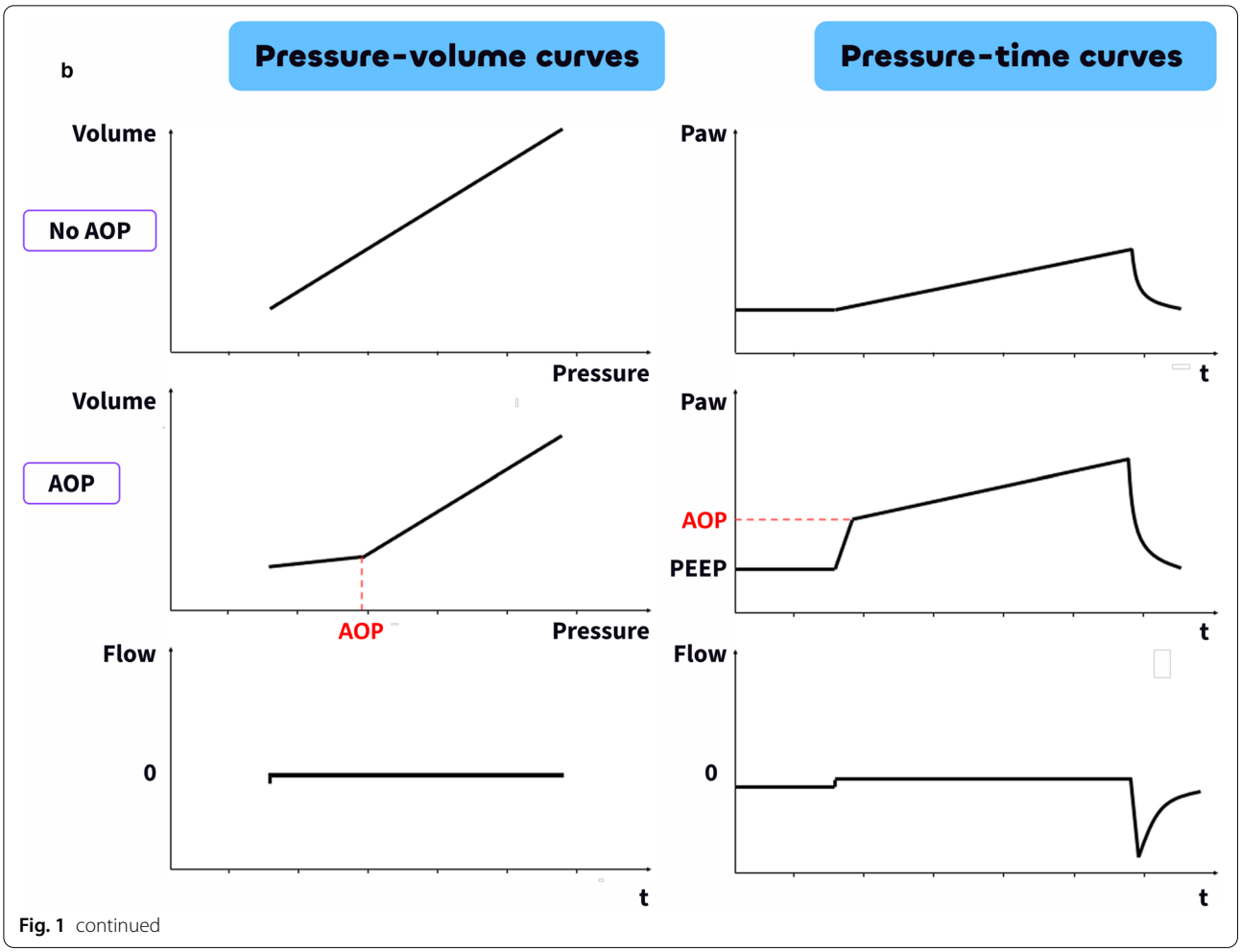

Fig. 1 continued

syndrome. According to the equation of motion, driving pressure equals tidal volume divided by C_{RS}. Because C_{RS} closely correlates with aerated lung volume [7, 8], driving pressure provides an estimate of lung strain, that is, tidal volume normalized to functional lung size. A driving pressure above 14 cmH_2O is associated with increased mortality [9]. Such a situation indicates that the delivered tidal volume is excessive relative to the available lung volume and should prompt a reduction in tidal volume if gas exchange allows. Because a decrease in tidal volume often requires a compensatory increase in respiratory rate to maintain carbon dioxide clearance, balancing minimization of driving pressure against avoidance of excessive respiratory rates when the driving pressure is low (i.e., below 10–12 cmH_2O) remains a matter of research [10–12].

Flow waveform during pressure-controlled ventilation

In pressure-controlled ventilation, airway pressure is fixed while flow varies according to respiratory mechanics. In this setting, analysis of the inspiratory flow waveform together with tidal volume monitoring allows indirect detection of changes in respiratory mechanics. For example, a lower peak inspiratory flow indicates higher R_{RS} or E_{RS}, whereas a steeper deceleration of flow during insufflation reflects increased E_{RS}. End inspiratory and end expiratory holds have the same physiological meaning as in volume-assist control ventilation. They allow measurement of plateau pressure and total PEEP and thus estimation of C_{RS} and E_{RS}, whereas R_{RS} cannot be directly measured.

Expiratory flow and the time constant of the respiratory system

In a passive patient, expired volume ($V_{exp}(t)$) follows an exponential decay:

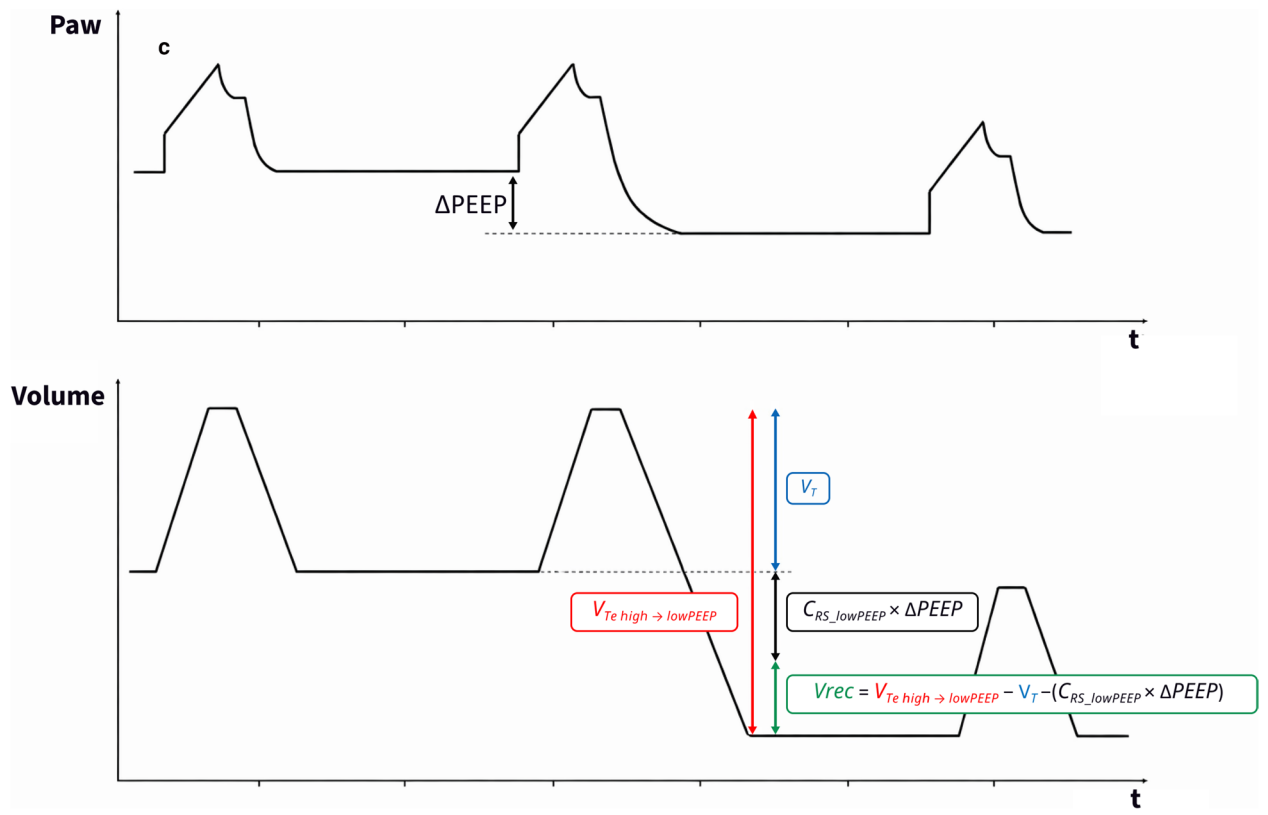

Fig. 1 continued

$$V_{\exp}(t) = V_{\mathrm{T}}.e^{-\frac{t}{\tau}}$$

where V_{T} is the tidal volume and τ is the expiratory time constant, defined as [13]:

$$\tau = C_{\mathrm{RS}} \times R_{\mathrm{RS}}$$

After three time constants, approximately 95% of V_{T} is exhaled. Higher C_{RS} and/or R_{RS} therefore prolong expiration. When expiratory time is insufficient relative to τ, expiration remains incomplete, causing dynamic hyperinflation and intrinsic PEEP. This can be detected when expiratory flow does not return to zero before the next insufflation. Intrinsic PEEP may also be suspected when $P_{\mathrm{cond}} > P_{\mathrm{res}}$ (Fig. 1A) and can be quantified by measuring total PEEP during an end expiratory occlusion maneuver.

Dynamic bedside maneuvers

Airway opening pressure (AOP)

The reference method for measuring the AOP on a ventilator is to perform a low-flow insufflation and examine the resulting pressure–volume or a pressure–time curve [2, 14]. In case of AOP above the PEEP level, the maneuver reveals an initial linear segment that reflects the compliance of the ventilator circuit (≈ 2.5 mL/cmH_2O), followed by a breakpoint corresponding to the AOP, and then a second linear segment representing the compliance of the respiratory system (Fig. 1B). When airway closure is identified, PEEP should be set at least at the level of the AOP.

Recruitability and the recruitment-to-inflation ratio

A single-breath maneuver can be used to estimate the volume recruited by PEEP at the bedside [15]. The maneuver consists of reducing the respiratory rate to approximately 10 bpm and then abruptly decreasing PEEP, typically from 15 to 5 cmH_2O (Fig. 1C). The expired volume collected during the breath corresponding to the transition from high to low PEEP ($V_{\mathrm{Te\ high \rightarrow lowPEEP}}$) contains three components: the tidal volume (V_{T}) delivered at high PEEP; the volume already aerated at low PEEP that was distended by the higher PEEP—a volume equal to the compliance at low PEEP ($C_{\mathrm{RS_lowPEEP}}$) multiplied by the change in PEEP (ΔPEEP)—and the volume that had been recruited at the higher PEEP level and is derecruited during this

maneuver. The recruited volume (V_{rec}) can therefore be calculated as follows:

$$V_{rec} = V_{Te\ high \rightarrow lowPEEP} - V_T - (C_{RS_lowPEEP} \times \Delta PEEP)$$

The recruitment-to-inflation ratio (R/I ratio) normalizes the potential benefit of PEEP—namely alveolar recruitment—to its mechanical cost, which is the inflation of the lung already open at low PEEP. It is obtained by dividing the compliance of the recruited volume ($V_{rec}/\Delta PEEP$) by $C_{RS_lowPEEP}$. Thus, the R/I ratio quantifies, for each additional cmH_2O of PEEP, the amount of recruited lung volume relative to the volume simply distended by increased PEEP. A low R/I ratio identifies patients with limited recruitability, in whom high PEEP strategies are unlikely to be beneficial and a low-PEEP approach is physiologically justified.

The way forward

Modern mechanical ventilators offer continuous, real-time access to respiratory physiology directly at the bedside. Careful interpretation of ventilator waveforms provides clinicians with essential physiological information at a glance, enabling optimization of ventilator settings. In addition, dynamic maneuvers allow the assessment of airway closure and lung recruitability, thereby guiding individualized PEEP titration. The frequency of ventilator screen assessment should be adapted to patient severity and clinical evolution. Given the potential clinical relevance of the information provided by ventilator waveform analysis, this assessment can be performed not only by physicians but also by appropriately trained nurses and respiratory therapists.

Author details
[1] Service de Médecine Intensive Réanimation, Assistance Publique-Hôpitaux de Paris, CHU Henri Mondor-Albert Chenevier, Créteil, France. [2] Groupe de Recherche Clinique CARMAS, Université Paris Est-Créteil, Créteil, France. [3] INSERM U 955, Institut Mondor de Recherche Biomédicale (IMRB), Créteil, France. [4] Department of Anesthesia, Critical Care and Emergency, Fondazione IRCCS Ca' Granda Ospedale Maggiore Policlinico, Milan, Italy. [5] Department of Anesthesia and Intensive Care Unit, Regional University Hospital of Montpellier, St-Eloi Hospital, University of Montpellier, Montpellier, France. [6] PhyMedExp, INSERM U1046, CNRS UMR, Montpellier, France.

Author contributions
GC, ES, and SJ were involved in conceptualization and writing. All authors read and approved the final manuscript.

Data availability
Not applicable.

Declarations

Conflicts of interest
GC received grants from the "programme hospitalier de recherche clinique national", and reports personal fees from Fisher & Paykel, Medtronic, Dräger, Air Liquide Medical Systems and GE Healthcare for lectures, outside the present work. ES declares no conflict of interest. SJ reports receiving consulting fees from Drager, Medtronic, Mindray, Baxter-Vantive, and Fisher & Paykel. SJ is the Editor in Chief of Intensive Care Medicine. He has not taken part in the review or selection process of this article.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Received: 23 December 2025 Accepted: 5 February 2026
Published online: 25 February 2026

References

1. Henderson WR, Chen L, Amato MBP, Brochard LJ (2017) Fifty years of research in ARDS. Respiratory mechanics in acute respiratory distress syndrome. Am J Respir Crit Care Med 196:822–833
2. Haudebourg A-F, Moncomble E, Lesimple A, Delamaire F, Louis B, Mekontso Dessap A et al (2023) A novel method for assessment of airway opening pressure without the need for low-flow insufflation. Crit Care 27:273
3. Rezoagli E, Pozzi M, Cereda M, Foti G (2023) Overestimation of driving pressure by the analysis of the conductive pressure during venous-arterial ECMO: airway closure or intrinsic PEEP? Crit Care 27:497
4. Grasso S, Terragni P, Mascia L, Fanelli V, Quintel M, Herrmann P et al (2004) Airway pressure-time curve profile (stress index) detects tidal recruitment/hyperinflation in experimental acute lung injury. Crit Care Med 32:1018–1027
5. Ranieri VM, Giuliani R, Fiore T, Dambrosio M, Milic-Emili J (1994) Volume-pressure curve of the respiratory system predicts effects of PEEP in ARDS: "occlusion" versus "constant flow" technique. Am J Respir Crit Care Med 149:19–27
6. Sun X-M, Chen G-Q, Chen K, Wang Y-M, He X, Huang H-W et al (2018) Stress index can be accurately and reliably assessed by visually inspecting ventilator waveforms. Respir Care 63:1094–1101
7. Gattinoni L, Marini JJ, Pesenti A, Quintel M, Mancebo J, Brochard L (2016) The, "baby lung" became an adult. Intensive Care Med 42:663–673
8. Gattinoni L, Pesenti A (2005) The concept of "baby lung." Intensive Care Med 31:776–784
9. Amato MBP, Meade MO, Slutsky AS, Brochard L, Costa ELV, Schoenfeld DA et al (2015) Driving pressure and survival in the acute respiratory distress syndrome. N Engl J Med 372:747–755
10. Costa ELV, Slutsky AS, Brochard LJ, Brower R, Serpa-Neto A, Cavalcanti AB et al (2021) Ventilatory variables and mechanical power in patients with acute respiratory distress syndrome. Am J Respir Crit Care Med 204:303–311
11. Haudebourg A-F, Tuffet S, Perier F, Razazi K, de Prost N, Mekontso Dessap A et al (2022) Driving pressure-guided ventilation decreases the mechanical power compared to predicted body weight-guided ventilation in the Acute Respiratory Distress Syndrome. Crit Care 26:185
12. Futier E, De Jong A, Cirenei C, Godet T, Jabaudon M, Constantin J-M et al (2025) Personalized driving pressure-guided positive end-expiratory pressure in patients at risk of postoperative respiratory failure (IMPROVE-2): a multicenter, pragmatic, randomized clinical trial. Intensive Care Med 51:1797–1808
13. Depta F, Kallet RH, Gentile MA, Kassis ENB (2025) Expiratory time constants in mechanically ventilated patients: rethinking the old concept—a narrative review. ICMx 13:40
14. Chen L, Del Sorbo L, Grieco DL, Shklar O, Junhasavasdikul D, Telias I et al (2018) Airway closure in acute respiratory distress syndrome: an underestimated and misinterpreted phenomenon. Am J Respir Crit Care Med 197:132–136
15. Chen L, Del Sorbo L, Grieco DL, Junhasavasdikul D, Rittayamai N, Soliman I et al (2020) Potential for lung recruitment estimated by the recruitment-to-inflation ratio in acute respiratory distress syndrome. A clinical trial. Am J Respir Crit Care Med 201:178–187